

Massive Connectivity in 5G and Beyond: Technical Enablers for the Energy and Automotive Verticals

Charalampos Kalalas and Jesus Alonso-Zarate
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA), Barcelona, Spain
Emails: {ckalalas, jesus.alonso}@cttc.es

Abstract—Massive machine-type communication (mMTC) is expected to revolutionize the fifth-generation (5G) and beyond-5G systems by enabling connectivity for a high number of low-rate low-power devices with sporadic activity patterns. To realize the full potential of mMTC, radical enhancements are required for the radio access design and the architecture of current cellular systems. In this paper, we discuss the mMTC peculiarities in the context of emerging energy and automotive use cases. We identify key mMTC challenges that hinder efficient and scalable connectivity in the smart grid and in vehicular communication. Representative technical enablers are then proposed aiming to tackle the massive connectivity limitations in various scenarios. The performance assessment of the presented approaches reveals the superior performance compared to the benchmark schemes while useful insights can be drawn for the design principles of future mMTC protocols. Finally, we discuss some key technology trends relevant to mMTC that are expected to provide a roadmap for the design of novel solutions to evolve post-5G connectivity.

Index Terms—5G, mMTC, IoT, smart grid, V2X, access class barring, grant-free, discovery, sidelink.

I. INTRODUCTION

Massive machine-type communication (mMTC) is expected to play an essential role in the context of the fifth-generation (5G) and beyond-5G wireless systems which, unlike previous generations, are designed to serve a number of industry verticals such as energy, automotive/transportation, healthcare, manufacturing, and many others. Emerging mMTC applications within the Internet-of-Things (IoT) paradigm, e.g., advanced smart metering infrastructure, ubiquitous vehicle-to-everything (V2X) connectivity, typically involve the transmission of short information payloads by a high number of network entities with sporadic activity patterns and without (or with a minimal) human interaction. Besides the high device density, these applications are often associated with unprecedented stringent requirements in terms of latency and reliability, that challenge the classical radio access design principles of cellular systems [1].

The fundamentally different characteristics of mMTC traffic render indispensable a major mentality shift on the way physical/medium-access-control (PHY/MAC) layer protocols are designed. In order to meet the performance targets of emerging mMTC applications, the third generation partnership project (3GPP) has been working on the development of novel and innovative PHY/MAC enhancements during the recent standard releases [2]–[4]. Following the successful finalization of 3GPP Rel-16, ongoing standardization efforts in the context of the new radio (NR) framework aim at: *i*) mitigating

congestion and signaling overhead in the radio access and core networks; *ii*) ensuring seamless connectivity in confined and coverage-limited areas with mMTC deployments; and *iii*) optimizing the contention-based uplink transmissions with minimum power consumption, access delay, and complexity. In particular, the focus of NR-mMTC is to complement the already powerful LTE-M and NB-IoT radio technologies (standardized during previous 3GPP releases) with the ability to operate within an NR carrier and exploit novel features such as: *i*) the narrower physical layer numerologies, i.e., subcarrier spacing; *ii*) the slot/mini-slot frame structure; *iii*) the operation in higher-frequency bands (even beyond 100GHz and THz frequencies); and *iv*) the sidelink interface enhancements [5], [6]. Due to its timeliness, the mMTC scalability problem has attracted extensive attention by the research community during the recent years [7].

In this context, this paper presents several technical approaches specifically tailored to address massive connectivity problems encountered in emerging energy and automotive use cases. The idiosyncrasies of the smart grid and V2X communication are taken into account and our proposed enablers aim to strike a balance in the triple scalability-reliability-delay tradeoff which requires a radical departure from conventional solutions. The performance assessment of the presented schemes against benchmark approaches under various metrics provides useful insights for the support of mMTC scenarios with stringent requirements. As 3GPP standardization work is underway towards enhancing connectivity in mMTC, the proposed approaches may also prove beneficial for other use cases envisioned for beyond-5G systems which rely on massive information acquisition.

Organization: The rest of the paper is organized as follows. Section II and III discuss mMTC-related challenges in the smart grid and V2X ecosystems, respectively, along with key technical enablers tailored to address the massive connectivity problem in these domains. Section IV provides a number of emerging technology trends expected to play pivotal roles in the design of novel mMTC solutions in the short term. Finally, Section V concludes the paper.

II. THE CONNECTED SMART GRID

The ongoing modernization of the aging electrical grid into a fully automated and interconnected smart grid heavily relies on the mMTC paradigm. In particular, two key building blocks have emerged for the realization of the smart grid during

the recent years: *i*) large-scale information acquisition and *ii*) reliable monitoring, protection and control. The former entails the massive installation of smart metering devices in deployments spanning broad geographical areas. The latter requires the use of intelligent electronic devices (IEDs) capable of exchanging mission-critical communication for real-time situational awareness and rapid detection of power system faults.

One of the major limitations towards scalable cellular connectivity for the smart grid stems from the deficiencies of the random access channel (RACH) procedure which involves signal exchange between each device and the base station (BS) for access reservation and connection establishment [8]. The limited random access opportunities (i.e., 64 RACH preambles) compared to the near-simultaneous access requests by a high number of smart meters render the standard RACH mechanism highly susceptible to congestion due to the high probability of collisions in the preamble transmission. Besides the RACH scalability issues for mMTC, the peculiar characteristics of smart grid traffic, ranging from low-rate smart metering information to event-driven protection data from IEDs with burst traffic-activation patterns, challenge the classical design principles of random access protocols.

As the traditional RACH connectivity paradigm is progressively rendered incapable of managing effectively the mMTC requirements in the smart grid, a radical reconsideration of the channel access procedure becomes necessary. In the following subsections, we present two representative technical enablers tailored to tackle RACH congestion issues in different smart grid use cases.

A. Dynamic Access Class Barring

In recent 3GPP standard releases, the access class barring (ACB) scheme has been adopted as an effective overload control mechanism to prevent access failures [9]. Two alternative barring mechanisms have been considered for ACB. The first method is based on dividing the devices into 10 access classes and applying the ON/OFF principle per access class. The second method is based on a probability value and a timer. In case of network overload, the BS broadcasts a barring rate factor and a barring timer for backoff. In turn, the devices generate a random number between 0 and 1 before the RACH attempt. If the random number is lower than the barring rate factor, the ACB test is passed and the device may attempt access. Otherwise, the device has to wait a given amount of time indicated by the backoff timer and draw a new random number before reattempting a new RACH access.

In the literature, numerous ACB variants have been proposed aiming to adapt ACB parameters and optimize relevant performance metrics using either static or adaptive approaches [10]–[12]. Based on the analytical framework proposed in [8], Fig. 1 depicts the performance comparison of the conventional RACH procedure (no ACB) with two different RACH-ACB approaches in terms of average success probability, defined as the probability to complete the RACH procedure in the maximum number of preamble transmissions. The first RACH-ACB

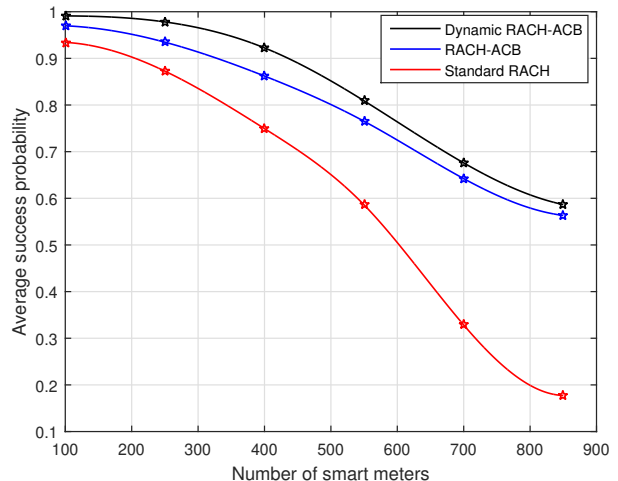


Fig. 1. Performance comparison of the dynamic and the standard RACH-ACB schemes with respect to the benchmark RACH procedure (no ACB) for increasing smart metering traffic load.

scheme follows an ACB-parameter configuration according to the standard specifications while the second one adopts a Q-learning approach aiming to dynamically tune the barring rate parameter according to the actual traffic load. In particular, using the average number of preamble transmissions per slot as the load indicator, the dynamic RACH-ACB scheme sets the barring rate to a more restrictive value as the number of devices increases in order to reduce the congestion. The updates of the barring rate values are periodically broadcast by the BS as part of the system information. As it can be observed in Fig. 1, the performance gains of the dynamic approach can be capitalized even in the high traffic regime.

B. Grant-free Access

Among the various techniques proposed for the enhancement of the RACH procedure, grant-free access schemes, where uplink transmissions can take place without a prior request-grant phase, are considered as a promising and low-overhead mechanism for smart grid operations involving mMTC [1]. Grant-free access can be well-suited in scenarios with event-driven smart grid traffic, e.g., power system fault detection, and rely on collision resolution using multiple-input multiple-output (MIMO) detection techniques at the BS side. Thus, grant-free access protocols aim to minimize the access delay compared to a signaling-intensive connection-establishment method at the cost of advanced interference mitigation techniques. Consequently, numerous variants of grant-free access protocols have been developed over the recent years [13]. Solutions based on central coordination and feedback capabilities are rendered insufficient for mission-critical applications where stringent delay deadlines have to be met. Another key consideration refers to the design of proper activity and multi-user detection algorithms to decode the useful data from the non-orthogonal superimposed signals.

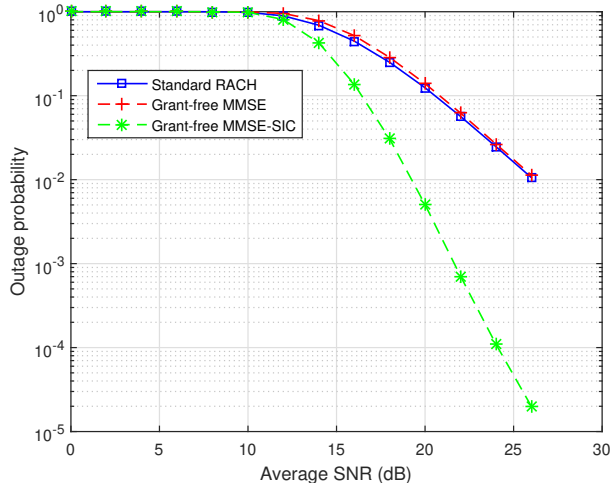


Fig. 2. Performance comparison of the standard RACH mechanism and the grant-free access schemes for different receiver types. The grant-free access schemes are configured with a relatively lower (nearly half) number of uplink resources compared to the standard case.

In an effort to demonstrate the benefits of a simplified grant-free access with respect to the conventional RACH procedure, Fig. 2 illustrates the reliability gains in terms of outage probability for receiver types of different complexity, i.e., minimum mean squared error (MMSE) and MMSE-successive interference cancellation (SIC) receivers. A shared slot assignment is considered for grant-free access where all available resources are shared by the transmitting IEDs. As it can be observed, a grant-free access scheme in combination with advanced MMSE-SIC receivers can substantially improve the reliability performance. In addition, this reliability gain is attained with relatively less number of uplink resources, compared to the conventional RACH case, which reveals the spectral efficiency of this approach. Although the substation automation scenario under consideration entails a quite low number of IEDs, the presented assessment can act as a baseline for more sophisticated grant-free access schemes addressing mMTC scenarios [14].

III. THE CONNECTED V2X ECOSYSTEM

During the recent years, the automotive industry is evolving towards an mMTC vision where vehicles become increasingly aware of their surroundings and capable of communicating with each other, with road-side units (RSUs), and with other road users, e.g., pedestrians, cyclists, etc. In this context, 5G and beyond-5G systems are expected to play a fundamental role towards a fully connected Internet-of-Vehicles (IoV) with ubiquitous V2X links [15]. The large-scale deployment of low-cost wireless sensors with integrated sensing, computing, and storing capabilities, offers the potential to transform vehicles into powerful computing and networking hubs towards increased road safety, optimized driving decision-making, and real-time traffic control. With an increasing level of driving automation, safety-critical services impose stringent

requirements in terms of end-to-end delay, reliability and positioning accuracy [16]. These requirements become even more challenging when considering the fast-varying nature of the V2X propagation environment and the ever-changing network topologies, as a consequence of the high vehicles' mobility. The V2X dynamics, including high Doppler and delay spread due to the moving transmitters, receivers, and scatterers, create a harsh propagation environment challenging V2X connectivity.

In the case of high-frequency operating bands, e.g., mmWave, for V2X communication, the improvement in terms of data rate may come at the expense of shadowing/blockage effects in the direct links to the RSUs or the BS. In addition, the cost of sophisticated transmit/receive antenna beam alignment techniques and channel state information (CSI) acquisition become non-negligible. In such harsh propagation environments, signaling overheads are costly and, as a consequence, the exploitation of the direct communication path among vehicles via the establishment of vehicle-to-vehicle (V2V) links over the sidelink interface is rendered indispensable. In addition, the localized nature of V2V data exchange can yield a dramatic end-to-end delay reduction which is of utmost importance in time-critical vehicular applications. In the following subsections, we focus on mMTC vehicular scenarios with high vehicle density and we present two technical enablers related to V2V connectivity establishment and data exchange over the sidelink interface.

A. Signature-based Vehicle Discovery

Vehicle discovery constitutes one of the essential procedures for the establishment of a V2V link and the realization of direct data exchange among vehicles. Vehicle discovery without network assistance is typically time and energy consuming, employing asynchronous scan/search mechanisms with beacon signals which often lead to underutilization of the scarce radio resources. In high-mobility and dense vehicular environments involving mMTC, contention-based vehicle discovery schemes suffer from uncontrolled collisions in the transmission of beacons which may compromise the reliability performance. On the other hand, network-assisted vehicle discovery can benefit from the underlying synchronization of the cellular infrastructure; however, the challenge in this case lies on the design of vehicle discovery techniques which can be readily applied to the existing cellular procedures without significant modification.

In [17], we proposed a vehicle discovery method where a discovery entity, residing at the BS, gathers information relevant to the proximity of the vehicles to discover V2V pairs. For coarse filtering of the network entities during the discovery procedure, we assume that each vehicle is interested in discovering only a part of its neighboring vehicles which reside within a predefined discovery distance D . Each vehicle is assumed to randomly select either a transmit (Tx) or a receive (Rx) state. The proposed scheme relies on the transmission of *i*) discovery signatures by Tx vehicles to their nearby Rx vehicles (within D) and *ii*) reporting signatures

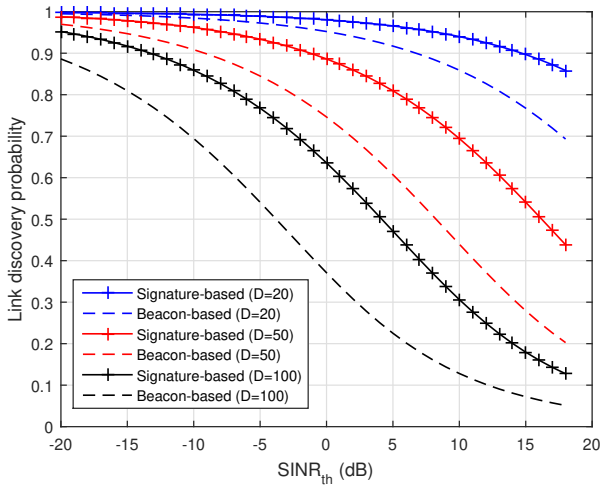


Fig. 3. Performance comparison of the signature-based and beacon-based discovery schemes for different discovery distance ranges.

by the activated Rx vehicles to the BS. Each signature constitutes a probabilistic data structure generated following Bloom filter principles [18] and contains the identification (ID) of the vehicle. The BS becomes aware of the proximity relations via reporting messages sent by the Rx vehicles which include information on the Tx vehicles' IDs received during a prior phase. To optimize the discovery scheme, the signature properties, i.e., the length of time slots and the number of required hash functions, can be dynamically tuned based on the network load to minimize the false-positive probability, i.e., the probability of an inactive signature being perceived as active. The proposed discovery mechanism therefore ensures that the resources for V2V data exchange are allocated in response to the number of discovered vehicle pairs, preventing the underutilization of the available spectrum. Fig. 3 illustrates the superior performance in terms of link discovery probability of our proposed scheme compared to a beacon-based discovery for different values of D .

B. Event-based Sidelink Resource Allocation

Depending on the assistance or involvement of the infrastructure in the management and control of communication, V2V transmissions can be either network-assisted or non-assisted, i.e., autonomously handled by the vehicles. Despite the benefits of the non-assisted V2V mode in out-of-coverage vehicular scenarios, network-assisted V2V communication can achieve a relatively better performance as a result of the superior resource allocation and interference management provided by a central entity [19]. Two main approaches have been considered for the radio resource management of sidelink communication: *i*) orthogonal allocation, where vehicles utilize mutually orthogonal parts of the spectrum to avoid interference and the main challenge resides in the efficient and fair partition of the radio resources to achieve increased spectrum efficiency; and *ii*) shared allocation, where vehicles share the data resources and the main challenge

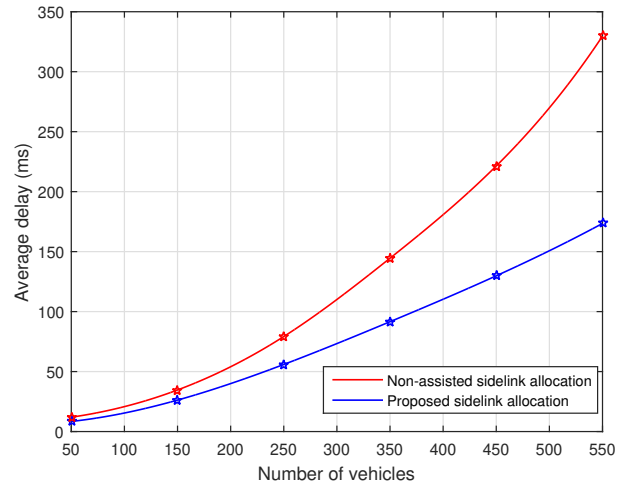


Fig. 4. Performance comparison of non-assisted and network-assisted event-based resource allocation schemes for the sidelink interface for increasing number of connected vehicles.

resides in the efficient intra-cell interference management. Several resource allocation alternatives have been proposed in the literature, ranging from power control and location-aware interference mitigation techniques to interference cancellation and time-frequency hopping schemes [20]–[22].

In [23], we proposed a generic dynamic resource allocation scheme tailored for event-triggered sidelink establishment upon detection of a mission-critical event in mMTC scenarios. In this scheme, the BS exploits the sidelink CSI, communicated by the vehicles via measurement reports during their initial network access, to properly allocate sidelink physical resources to subsets of neighboring vehicles. Upon detection of an event, e.g., emergency braking of the preceding vehicle in a platoon formation, based on the resulting RACH overload at the BS, the vehicles are signalled to use the resource pool dedicated to their sidelink transmissions. In turn, the vehicles located in close proximity to each other exploit the spatial reuse gain and mitigate the mutual interference from nearby vehicles with the aid of their multi-antenna reception capabilities. Fig. 4 reveals the average delay gains of our proposed scheme compared to an autonomous (i.e., non-assisted) resource allocation for sidelink for increasing vehicle traffic load.

IV. KEY TECHNOLOGY TRENDS FOR mMTC

As 3GPP standardization work is underway and the transition towards 5G systems is emerging, mMTC is anticipated to provide a strong foundation for unprecedented use cases in the short term. In what follows, we highlight three key mMTC-related technology trends that receive growing research attention nowadays and may substantially steer post-5G connectivity principles.

- 1) *Exploitation of massive data availability*: Artificial Intelligence/Machine Learning (AI/ML) techniques are able to build on the massive amounts of data and identify features

that could enable the interaction with the underlying radio protocols. By unlocking the potential value of data, robust data-driven channel access techniques could be developed beyond the conventional model-based or algorithmic solutions. This approach is in line with the ongoing 3GPP study item on "RAN-centric data collection and utilization for NR" which aims at broadening the set of standard-based solutions for enhanced data collection and utilization capabilities, including RACH optimization as an application under investigation [24].

- 2) *Accurate traffic characterization for mMTC*: Novel traffic modeling approaches are necessary in order to extract the special properties of mMTC traffic, e.g., context dependencies, spatiotemporal correlation, etc., and render the subsequent data transmission more meaningful. The mMTC data often exhibit non-stationary behaviour over small window sizes, rendering indispensable the use of accurate techniques for estimating their traffic generation patterns [23]. However, due to their sporadic and bursty nature, mMTC traffic modeling may result in multimodal probability distributions that are hard to be modelled with reference traffic models.
- 3) *Explore the potential of the smart radio environment*: The emerging reconfigurable intelligent surfaces (RISs) consist of programmable nearly passive elements, each of which can be properly tuned to apply arbitrary phase shifts to the impinging radio signals and mitigate the wireless propagation impairments [25]. As the transition towards high-frequency bands, namely millimeter and sub-millimeter wave frequencies, is underway, the applicability of RISs could be explored in the context of mMTC as a promising and low-cost solution to provide link diversity and achieve reliable uplink connectivity.

V. CONCLUSIONS

One of the fundamental challenges for 5G and beyond-5G systems is the scalable and efficient support of mMTC services. In this paper, we summarize several approaches to address the massive connectivity limitations in the energy and automotive verticals. The presented approaches aim to tackle scalability issues in highly dense scenarios while satisfying the stringent performance constraints. As mMTC constitutes a key innovation area for upcoming 3GPP standardization releases, the proposed enablers may have the potential to substantially steer future protocol design principles by identifying robust techniques that lead to higher protocol performance. Key technology trends which are expected to drive novel connectivity solutions for mMTC in beyond-5G systems are also outlined.

ACKNOWLEDGMENT

This work has been partially supported by the H2020-5GCAR project under Grant agreement No. 761510, by the CHIST-ERA FIREMAN project funded by the Spanish national foundation (PCI2019-103780), by the Spanish MINECO project SPOT5G (TEC2017-87456-P), and by the Generalitat de Catalunya under Grant 2017 SGR 891.

REFERENCES

- [1] C. Bockelmann *et al.*, "Towards Massive Connectivity Support for Scalable mMTC Communications in 5G Networks," *IEEE Access*, vol. 6, pp. 28969–28992, 2018.
- [2] 3GPP TS 22.368, "Service requirements for Machine-Type Communications (MTC)," 2014.
- [3] 3GPP TR RP-151186, "Further LTE Physical Layer Enhancements for MTC," 2015.
- [4] 3GPP TS 22.261, "Service requirements for the 5G system," 2017.
- [5] 3GPP TS 38.211, "NR; Physical channels and modulation," April 2018.
- [6] 3GPP TS 38.321, "NR; Medium Access Control (MAC) protocol specification," June 2018.
- [7] Z. Dawy, W. Saad, A. Ghosh, J. G. Andrews, and E. Yaacoub, "Toward Massive Machine Type Cellular Communications," *IEEE Wireless Communications*, vol. 24, pp. 120–128, February 2017.
- [8] C. Kalalas and J. Alonso-Zarate, "Reliability analysis of the random access channel of LTE with access class barring for smart grid monitoring traffic," in *IEEE International Conference on Communications Workshops (ICC Wkshps)*, pp. 724–730, May 2017.
- [9] 3GPP TS 36.331, "Radio Resource Control (RRC), Protocol Specification," September 2017.
- [10] H. S. Jang, H. Jin, B. C. Jung, and T. Q. S. Quek, "Recursive Access Class Barring for Machine Type Communications with PUSCH Resource Constraints," in *2019 IEEE International Conference on Communications (ICC)*, pp. 1–6, May 2019.
- [11] M. Lee, Y. Kim, Y. Piao, and T. Lee, "Recycling Random Access Opportunities with Secondary Access Class Barring," *IEEE Transactions on Mobile Computing*, pp. 1–1, 2019.
- [12] C. Di, B. Zhang, Q. Liang, S. Li, and Y. Guo, "Learning automata-based access class barring scheme for massive random access in machine-to-machine communications," *IEEE Internet of Things Journal*, vol. 6, pp. 6007–6017, August 2019.
- [13] L. Dai, B. Wang, Z. Ding, Z. Wang, S. Chen, and L. Hanzo, "A Survey of Non-Orthogonal Multiple Access for 5G," *IEEE Communications Surveys Tutorials*, vol. 20, pp. 2294–2323, Third Quarter 2018.
- [14] M. Mohammadkarimi, M. A. Raza, and O. A. Dobre, "Signature-based nonorthogonal massive multiple access for future wireless networks: Uplink massive connectivity for machine-type communications," *IEEE Vehicular Technology Magazine*, vol. 13, pp. 40–50, December 2018.
- [15] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, and L. Zhao, "Vehicle-to-Everything (v2x) Services Supported by LTE-Based Systems and 5G," *IEEE Communications Standards Magazine*, vol. 1, no. 2, pp. 70–76, 2017.
- [16] 3GPP TS 22.186, "Service requirements for enhanced V2X scenarios," 2017.
- [17] 5GCAR, "Deliverable D3.3: Final 5G V2X Radio Design," May 2019.
- [18] B. H. Bloom, "Space/Time Trade-offs in Hash Coding with Allowable Errors," *Communications of the ACM*, vol. 13, pp. 422–426, 1970.
- [19] R. Molina-Masegosa and J. Gozalvez, "LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications," *IEEE Vehicular Technology Magazine*, vol. 12, pp. 30–39, December 2017.
- [20] N. Cheng, H. Zhou, L. Lei, N. Zhang, Y. Zhou, X. Shen, and F. Bai, "Performance Analysis of Vehicular Device-to-Device Underlay Communication," *IEEE Transactions on Vehicular Technology*, vol. 66, pp. 5409–5421, June 2017.
- [21] Q. Ye, M. Al-Shalash, C. Caramanis, and J. Andrews, "Resource Optimization in Device-to-Device Cellular Systems Using Time-Frequency Hopping," *IEEE Transactions on Wireless Communications*, vol. 13, pp. 5467–5480, October 2014.
- [22] W. Sun, D. Yuan, E. G. Ström, and F. Brännström, "Cluster-Based Radio Resource Management for D2D-Supported Safety-Critical V2X Communications," *IEEE Transactions on Wireless Communications*, vol. 15, pp. 2756–2769, April 2016.
- [23] C. Kalalas, J. Alonso-Zarate, and G. Bag, "On the Transmission Mode Selection for Substation Automation Traffic in Cellular Networks," in *IEEE International Conference on Smart Grid Communications (Smart-GridComm)*, pp. 1–7, October 2017.
- [24] 3GPP TR 37.816, "Study on RAN-centric data collection and utilization for LTE and NR (Release 16)," 2019.
- [25] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753–116773, August 2019.